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Specification for Evaporation Duct Height Calculations

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The evaporation ducting phenomenon, the meteorological measurements required to assess its characteristics, and the algorithms to calculate its strength are described. The algorithms are developed in detail, a FORTRAN 77 computer listing is provided, and test cases to ascertain the proper operation of the program are specified.

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CONTENTS

1.0 INTRODUCTION

The purpose of this report is to document an evaporation duct model for inclusion as a Navy standard model in the Oceanographic and Atmospheric Master Library (OAML).

The propagation of microwaves at altitudes close to the surface of the sea depends upon the refractive structure in the first few tens of meters. This height interval is called the atmospheric surface layer and is usually dominated by mechanical and buoyant turbulence. The average profile of wind, temperature, humidity, or any scalar is determined by the turbulent motions. Roll[1] presents an overview of the wind, temperature, and moisture fields in the first few meters above the sea surface. Meteorological measurements to directly determine these profiles in the surface layer over the ocean are quite difficult and essentially impractical on an operational basis. To circumvent this difficulty, semiempirical relationships between the profiles and the fluxes of momentum, heat, and moisture have been developed.

For radio purposes, the profile of potential refractivity in the surface layer is of interest, with potential refractivity defined by

$$N_p = \frac{77.6\ P_o}{\theta} + 3.73 \times 10^5\ \frac{e_p}{\theta^2}$$

where $P_O = 1000$ mb, θ is potential temperature in Kelvin, and e_p is potential vapor pressure in mb. Further

$$\theta = T\left(\frac{P_o}{P}\right)^{0.286}$$

and

$$e_p = e\left(\frac{P_o}{P}\right)$$

where T is temperature in Kelvin, P is pressure in mb, and e is vapor pressure in mb. Over the ocean, the profile of potential refractivity is greatly shaped by the presence of trapping gradients, which form a shallow duct, called the evaporation duct because of the predominant influence of evaporation in causing the trapping gradients. The parameter that best characterizes propagation is the evaporation duct height, defined as the height at which the gradient of potential refractivity reaches the critical value, calculated by ray theory, which will cause a ray launched horizontally to have a curvature exactly equal to the curvature of the earth. In terms of modified refractivity, M, the evaporation duct height, δ, is the height in the surface layer at which the M profile reaches its minimum value and $dM/dz = 0$. Figure 1 is an example of an M profile for a 13-meter evaporation duct, which is near the world average duct height.

There are several semiempirical techniques to relate surface layer profiles to meteorological measurements that can be simply made at sea (often called bulk measurements). Jeske examined several schemes and correlated evaporation duct height to propagation measurements.[2-4] His work, with modifications,[5-7] is the basis for the duct height formulation later in this report; this formulation is developed in more detail in Appendixes A, B, and C. A FORTRAN 77 program is provided in Appendix D. Rotheram[8] has developed a similar formulation in a slightly different manner.

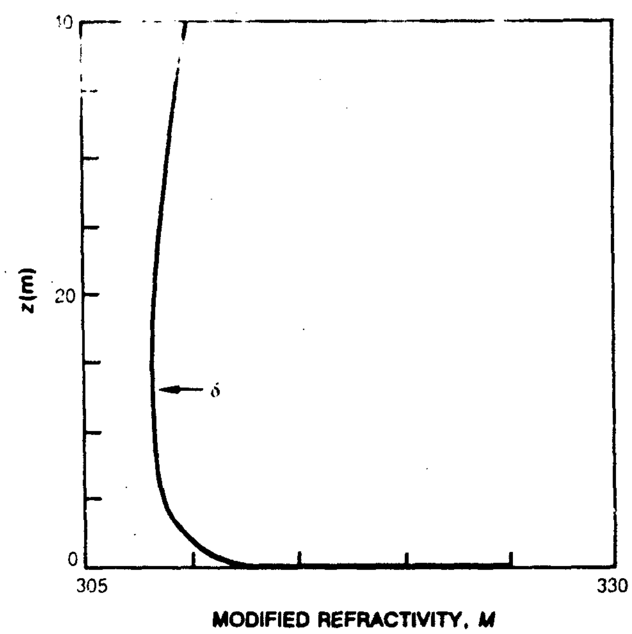

Figure 1. Example of a modified refractivity profile for a 13-meter evaporation duct. At the surface $M = 325$; z is the altitude.

2.0 INPUTS, OUTPUTS, AND LIMITS

The bulk meteorological measurements required for the evaporation duct calculation are wind speed, air and sea temperature, relative humidity, and altitude of the measurements. Since gradients in the surface layer generally become small at altitudes more than a few meters, the influence of measurement altitude is neglected as long as measurements are made at least 6 meters above the surface. Additionally, the influence of sea waves on the measurements is usually restricted to altitudes less than three times the wave height (Ref. 6, p. 123, and Ref. 9), and the altitude of 6 meters or greater minimizes most wave effects.

The inputs, outputs, and limits are discussed in the following paragraphs and are summarized in Table 1.

Table 1. Summary of inputs. outputs, and limits.

Parameter	Type	Limit	Precision
Wind speed	input	0 to 50 kt	1 kt
Air temperature	input	–20° to 50°C	0.1°C
Relative humidity	input	0 to 100%	1%
Sea temperature	input	0° to 40°C	0.1°C
Evaporation duct height	output	0 to 40 m	0.1 m

2.1 Wind Speed

Wind speed can be measured with the typical cup or aerovane anemometer. The anemometer should be mounted so as to minimize the disturbance to air flow caused by the observing platform. On a ship or a boat, the anemometer should be mounted as far forward and as high as possible; the measured relative wind must be corrected for ship's course and speed to determine true wind. Hand-held anemometers can also be used successfully if carried to the windward side of the platform.

The wind speed should be averaged over a period of 5 to 10 minutes. This will average out the turbulent fluctuations in wind speed. Wind speed input is limited to 0 to 50 knots.

2.2 Air Temperature and Relative Humidity

Measurement of air temperature and relative humidity can be made at any well-exposed site above an altitude of 6 meters with reasonable precautions taken to minimize platform-induced conductive and radiative heating. An aspirated psychrometer with wet and dry bulb thermometers is a convenient portable instrument. Since temperature and humidity gradients above 6 meters in the typical overwater surface layer are quite small, averaging times for these parameters can be 3 to 5 minutes. Air temperature input is limited to –20° to 50°C; relative humidity input is limited to 0 to 100%.

2.3 Sea Surface Temperature

The simplest measurement of sea surface temperature is made with a small rubber bucket (or any container with a small thermal mass) and an accurate thermometer. More durable, specifically designed water thermometer buckets are available which provide a frame for a thermometer and a small reservoir (bucket) to retain water around the thermometer bulb. These devices are used to sample the water over a finite depth (~ 0.3 meter). Under most conditions, the wind is sufficient to mix the upper levels of the water column (>2 meters). However, on cloudless days with strong solar heating and light winds, the surface temperature can vary considerably from the underlying water. In these instances, care must be taken to get a representative sample of the surface water.

Infrared radiometer sensors provide a remote means to sense the sea surface temperature. Although considerably more expensive than the buckets, they do have the advantage of sensing only the sea surface. If this sort of instrument is used, it should have a means to compensate for reflected sky radiation. Sea temperature input is limited to 0° to 40°C.

2.4 Evaporation Duct Height

Based on the inputs of wind speed, air temperature, relative humidity, and sea surface temperature, the evaporation duct height is calculated as the only output. For purposes of propagation assessment, the evaporation duct height is not a height below which an antenna must be located to give enhanced ranges but rather a parameter indicative of the strength of the evaporation duct. Strong evaporation ducts (high duct heights) will affect surface-to-surface propagation at frequencies as low as 1 to 2 GHz. Weak evaporation ducts (low duct heights) will affect only higher frequencies. The limits on evaporation duct height are 0 to 40 meters.

3.0 MODEL

The following six steps specify the calculation of evaporation duct height:

1. The four bulk meteorological measurements required are air temperature, T_a, and sea temperature, T_s, in Celsius; relative humidity, **RH**, in percent; and wind speed, u, in knots. Temperatures are converted to Kelvin by $T_{ak} = T_a + 273.2$ and $T_{sk} = T_s + 273.2$. If wind speed is less than 0.01 knot, evaporation duct height is set to 0 meters.

2. The bulk Richardson number is calculated by

$$Ri_b = 369\, z_1\, (T_{ak} - T_{sk}) \;/\; (T_{ak}\, u^2)$$

where z_1 is the reference height in meters. Ri_b is restricted to be no greater than 1.

3. Assuming that, in the surface layer, $T_{ak} \approx \theta$, $e \approx e_p$, and neglecting the effect of salinity on vapor pressure, calculate potential refractivity for the air, N_A, at height z_1 and for the air immediately in contact with the sea surface, N_S:

$$N_A = \frac{77.6}{T_{ak}} \left(1000 + \frac{4810}{T_{ak}}\, e \right)$$

$$N_S = \frac{77.6}{T_{sk}} \left(1000 + \frac{4810}{T_{sk}}\, e_0 \right)$$

where the ambient vapor pressure of the air, e, is calculated by

$$e = \frac{RH}{100}\, e_s$$

with

$$e_s = 6.105 \exp \left(25.22 \, \frac{T_{ak} - 273.2}{T_{ak}} - 5.31 \ln \frac{T_{ak}}{273.2} \right)$$

and the vapor pressure at the sea surface, e_0, is

$$e_0 = 6.105 \exp \left(25.22 \, \frac{T_{sk} - 273.2}{T_{sk}} - 5.31 \ln \frac{T_{sk}}{273.2} \right)$$

4. For thermally neutral and stable conditions ($0 \leq Ri_b \leq 1$), the evaporation duct height, δ, is calculated by

(a) $\delta = 0$ for $\Delta N_P \geq 0$

or

(b) $$\delta = \frac{\Delta N_p}{b_1 \ B - \Delta N_p \ \frac{a}{L'}}$$

or, if the result of (b) is such that $\delta < 0$ or $\delta/L' > 1$, then

(c) $$\delta = \frac{\Delta N_p(1 + a) - b_1 \ a \ z_1}{b_1 \ \ln \left(\frac{z_1}{z_0}\right)}$$

For stable conditions, the function B is

$$B = \ln \left(\frac{z_1}{z_0}\right) + \frac{a \ z_1}{L'}$$

5. For thermally unstable conditions ($Ri_b < 0$), evaporation duct height, δ, is calculated by

$$\delta = \left[\left(\frac{b_1 B}{\Delta N_p}\right)^4 - 4\frac{\beta}{L'}\left(\frac{b_1 B}{\Delta N_p}\right)^3\right]^{-\frac{1}{4}}$$

and the function, B, is

$$B = \ln \left(\frac{z_1}{z_0}\right) - \psi$$

The universal function, ψ, is determined by

$\psi = -4.5 \ \frac{z_1}{L'}$	$\frac{z_1}{L'} \geq -0.01$
$\psi = 10^{\left[1.02 \ \log \left(\frac{-z_1}{L'}\right) + 0.69\right]}$	$-0.01 > \frac{z_1}{L'} \geq -0.026$
$\psi = 10^{\left[0.776 \ \log \left(\frac{-z_1}{L'}\right) + 0.306\right]}$	$-0.026 > \frac{z_1}{L'} \geq -0.1$
$\psi = 10^{\left[0.630 \ \log \left(\frac{-z_1}{L'}\right) + 0.16\right]}$	$-0.1 > \frac{z_1}{L'} \geq -1$
$\psi = 10^{\left[0.414 \ \log \left(\frac{-z_1}{L'}\right) + 0.16\right]}$	$-1 > \frac{z_1}{L'} \geq -2.2$
$\psi = 2$	$\frac{z_1}{L'} < -2.2$

6. The maximum value of evaporation duct height is limited to 40 meters. Remaining variables and constants are defined as follows:

ΔN_p = $N_A - N_S$, potential refractivity difference between the air and the sea

z_1 = 6 meters, reference height

b_1 = $-0.125\ \mathrm{m}^{-1}$, critical gradient of potential refractivity

z_0 = 1.5×10^{-4}m , surface roughness parameter

β = 4.5 , coefficient in the unstable function

a = 5.2 , coefficient in the stable function

L' = $\dfrac{10 z_1 \Gamma_e}{Ri_b}$ m, Monin-Obukhov length, where

$\Gamma_e = 0.05$	$Ri_b \leq -3.75$
$\Gamma_e = 0.065 + 0.004\ Ri_b$	$-3.75 < Ri_b \leq -0.12$
$\Gamma_e = 0.109 + 0.367\ Ri_b$	$-0.12 < Ri_b \leq 0.14$
$\Gamma_e = 0.155 + 0.021\ Ri_b$	$0.14 < Ri_b$

The dominant factor in determining evaporation duct height is the difference in potential refractivity between the air at the reference height and the air at the sea surface. Errors in air temperature measurement caused by conductive and radiative heating effects have been shown to strongly affect the duct height calculation.[7] To minimize the sensitivity of the evaporation duct algorithm, an additional test is applied whenever $T_a - T_s > -1$. Evaporation duct height is calculated for $T_a = T_s$, (δ_o), and for $T_a = T_s - 1$, (δ_{-1}), with T_s , u, and RH unchanged. Then, if $\delta_o > \delta_{-1}$, the value of δ_{-1} is the evaporation duct height; otherwise, the evaporation duct height is calculated as defined in steps 1 through 6 above.

4.0 TEST CASES FOR CALCULATION OF EVAPORATION DUCT HEIGHT

Table 2 lists data that can be used to verify the proper implementation of the computer program in Appendix D. For the specified inputs of air temperature (°C), sea temperature (°C), relative humidity (%), and wind speed (knots), the evaporation duct height should be calculated correctly to within ±0.1 meter.

Table 2. Test inputs and evaporation duct height (δ) outputs.

T_a (°C)	T_s (°C)	RH (%)	u (knots)	δ (m)
0.0	15.0	10	1	3.9
0.0	15.0	10	20	16.8
0.0	15.0	75	1	2.8
0.0	15.0	75	20	12.3
0.0	15.0	100	1	2.4
0.0	15.0	100	20	10.4
0.0	16.0	10	1	4.0
0.0	16.0	10	20	17.3
0.0	16.0	75	1	3.0
0.0	16.0	75	20	13.0
0.0	16.0	100	1	2.6
0.0	16.0	100	20	11.2
15.0	15.0	10	1	8.7
15.0	15.0	10	20	37.0
15.0	15.0	75	1	3.6
15.0	15.0	75	20	13.9
15.0	15.0	100	1	0.0
15.0	15.0	100	20	0.0
15.0	16.0	10	1	9.1
15.0	16.0	10	20	38.8
15.0	16.0	75	0	0.0
15.0	16.0	75	1	3.8
15.0	16.0	75	20	14.6
15.0	16.0	100	1	0.9
15.0	16.0	100	20	2.6
30.0	15.0	10	1	8.7
30.0	15.0	10	20	37.0
30.0	15.0	75	1	3.6
30.0	15.0	75	20	13.9
30.0	15.0	100	1	0.0
30.0	15.0	100	20	0.0
30.0	16.0	10	1	9.1
30.0	16.0	10	20	38.8
30.0	16.0	75	1	3.8
30.0	16.0	75	20	14.6
30.0	16.0	100	1	0.0
30.0	16.0	100	20	0.0

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Appendix A

DEVELOPMENT OF THE EVAPORATION DUCT HEIGHT FORMULATION

References A-1 to A-3 provide a detailed development of the evaporation duct height formulation by Jeske. A general development of Jeske's formulation is included here along with assumptions and rationale for the implementation in the computer program listing in Appendix D.

Jeske defined the gradient

$$\frac{\partial \iota}{\partial z} = \frac{S_\iota}{\varrho \, \kappa \, u_* \, (z + z_o)} \phi \tag{A-1}$$

where ι is a scalar property of the atmosphere, S_ι is the vertical flux of ι, z is height in meters, κ is von Karmen's constant (0.4), u_* is the friction velocity in m/s, z_o is the roughness parameter in meters, and ϕ is a stability-dependent function (equal to 1 at thermally neutral conditions, i.e., air temperature equal to sea surface temperature). For stable conditions (air warmer than water), the stability function was taken to be the logarithmic-linear model proposed by Monin and Obukhov

$$\phi\left(\frac{z}{L'}\right) = 1 + a\frac{z}{L'} \tag{A-2}$$

where a is taken to be 5.2 and L' is the gradient form of the Monin-Obukhov scaling length corrected for stability. For unstable conditions (water warmer than air), the KEYPS relationship

$$\phi^4 - 4\,a\frac{z}{L'}\,\phi^3 = 1 \tag{A-3}$$

with $a = 4.5$ is used. To evaluate z/L', the bulk Richardson number is used as

$$Ri_b = \frac{g\,\Delta T\, z}{T\, u^2\, \Gamma} \tag{A-4}$$

where $g = 9.8$ m/s^2, z is height in meters, T is air temperature in Kelvin, ΔT is air temperature minus sea temperature, u is wind speed in m/s, and Γ is the profile coefficient. Ri_b involves approximating gradients with differences and assumes $T \approx \theta$ in the surface layer. The profile coefficient for neutral conditions is

$$\Gamma = \frac{1}{\ln\left(\frac{z_1 + z_o}{z_o}\right)} \tag{A-5}$$

and is approximately 0.1 for typical observation heights, z_1, and surface roughness parameter values, z_o, of 0.00015 meter. Similarly, L' is

$$L' = \frac{T u^2 \Gamma_e}{g \Delta T} \quad \text{(A-6)}$$

or, in terms of Ri_b

$$\frac{1}{L'} = \frac{Ri_b}{10 \, z_1 \, \Gamma_e} \quad \text{(A-7)}$$

where Γ_e is an empirical profile coefficient for nonneutral conditions (Fig. A-1). Γ_e is evaluated by a straight-line-segment fit to the data in Fig. A-1.

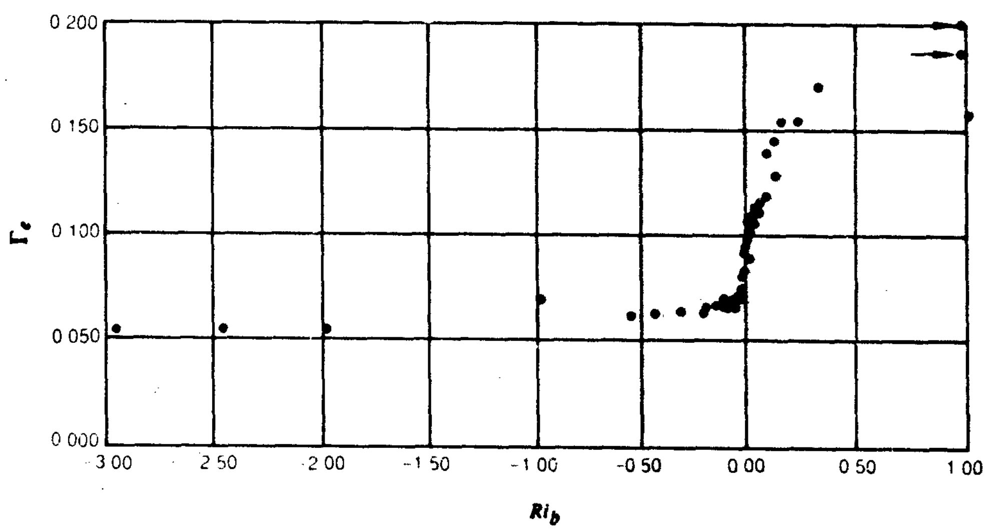

Figure A-1. The profile coefficient, Γ_e, as a function of bulk Richardson number, Ri_b (from Jeske [A-1 through A-3]).

Returning to Eq. A-1, assume the flux, S_i, is constant with height and integrate from the sea surface to z_1:

$$s_1 - s_o = \Delta s_1 = \frac{S_i}{\varrho \, \kappa \, u_*} \int_0^{z_1} \frac{\phi}{z + z_o} dz \quad \text{(A-8)}$$

Thus, the flux term is

$$\frac{S_\iota}{\varrho \kappa u_*} = \frac{\Delta\iota_1}{\int_0^{z_1} \frac{\phi}{z+z_o} dz} \tag{A-9}$$

and substituting in Eq. A-1 yields

$$\frac{\partial \iota}{\partial z} = \frac{\Delta\iota\, \phi}{B(z + z_o)} \tag{A-10}$$

where

$$B = \int_0^{z_1} \frac{\phi}{z+z_o} dz \tag{A-11}$$

Taking the scalar ι as potential refractivity, N_p, the height, δ, at which the critical gradient of potential refractivity ($b_1 = -0.125\ \mathrm{m}^{-1}$) occurs is found from Eq. A-10 as

$$\delta = \frac{\Delta N_p}{b_1 B - \Delta N_p \dfrac{a}{L'}} \tag{A-12}$$

where ϕ for stable conditions is determined from Eq. A-2 and B is evaluated as

$$B = \ln\frac{z_1}{z_o} + \frac{a}{L'} z_1 \tag{A-13}$$

Jeske recommends that δ/L' should not exceed 1. If this occurs, then duct height should be recalculated with $\delta/L' = 1$.

For unstable conditions, solving Eq. A-10 for ϕ in terms of N_p, substituting in Eq. A-3 with $z = \delta$, and solving yields

$$\delta = \left[\left(\frac{b_1 B}{\Delta N_p}\right)^4 - \frac{4a}{L'}\left(\frac{b_1 B}{\Delta N_p}\right)^3\right]^{-\frac{1}{4}} \tag{A-14}$$

where B is evaluated as

$$B = \ln\frac{z_1}{z_o} - \psi\left(\frac{z_1}{L'}\right) \tag{A-15}$$

$\psi(z_1/L')$ has the analytic form[A-4]

$$\psi = 1 - \phi - 3\ \ln\phi + 2\ \ln\left(\frac{1+\phi}{2}\right) + 2\ \tan^{-1}\phi - \frac{\pi}{2} + \ln\left(\frac{1+\phi^2}{2}\right) \tag{A-16}$$

Use of Eq. A-16 requires the iterative solution of Eq. A-3 for ϕ with a given z/L'. ψ can be more quickly determined by a straight-line-segment fit to the KEYPS profile of Fig. A-2 adapted from Lumley and Panofsky.[A-5]

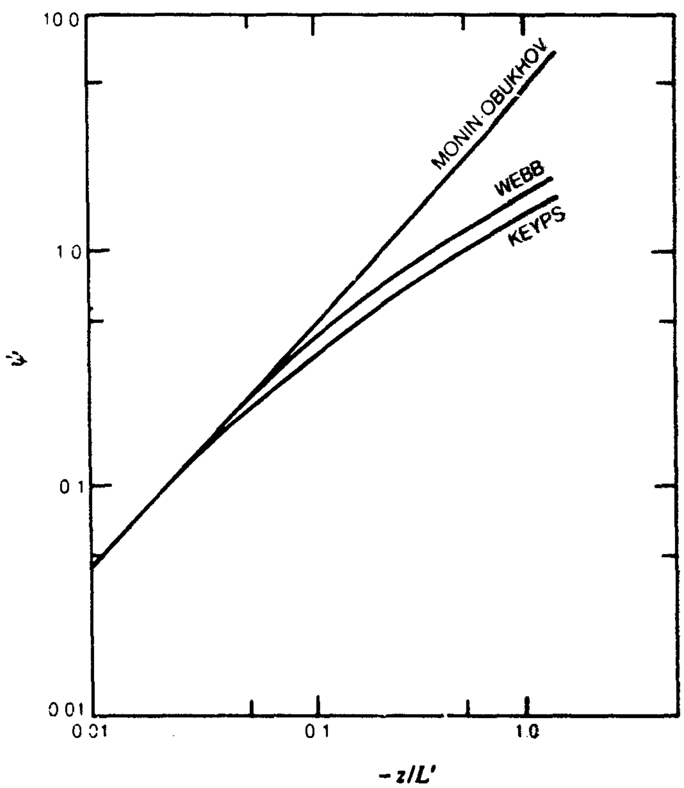

Figure A-2. Universal function ψ as a function of z/L' (from Lumley and Panofsky[A-5]).

REFERENCES TO APPENDIX A

A-1. Jeske, H., "Die Ausbreitung elektromagnetischer Wellen im cm- bis m-Band über dem Meer unter besonderer Berücksichtigung der meteorologischen Bedingungen in der maritimen Grenzschicht," *Hamburger Geophysikalische Einzelschriften*, De Gruyter, Hamburg, 1965.

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Appendix B

CRITICAL GRADIENT OF POTENTIAL REFRACTIVITY

The equation for refractivity in terms of pressure, P, in mb, temperature, T, in Kelvin, and water vapor pressure, e, in mb is

$$N = \frac{77.6\ P}{T} + 3.73 \times 10^5 \frac{e}{T^2} \tag{B-1}$$

For application in the atmospheric surface layer, potential refractivity

$$N_p = \frac{77.6\ P_o}{\theta} + 3.73 \times 10^5 \frac{e_p}{\theta^2} \tag{B-2}$$

is the conservative property where P_o is a reference pressure level (taken to be 1000 mb), θ is potential temperature, and e_p is potential water vapor pressure.

From geometric optics, the critical gradient required for trapping is that which yields a ray curvature equal to the earth's curvature

$$\frac{dN}{dz} = -\frac{10^6}{a} = -0.157\ N/m \tag{B-3}$$

where a is the earth's radius, 6371×10^3 meters. To relate the gradient of potential refractivity to the gradient of refractivity, take the total derivatives of $N_p(\theta, e_p)$ and $N(P, T, e)$ with respect to z. Assuming $\theta \approx T$ and $e_p \approx e$ in the surface layer yields

$$\frac{dN_p}{dz} = \frac{dN}{dz} - \frac{\partial N}{\partial P}\frac{dP}{dz} \tag{B-4}$$

The partial derivative $\partial N/\partial P = 77.6/T$ varies from 0.28 to 0.26 mb^{-1} over the range of temperature 0° to 30°C. The derivative dP/dz can be evaluated by making the hydrostatic approximation

$$\frac{dP}{dz} = -\varrho g = -\frac{Pg}{RT} \tag{B-5}$$

where ϱ is density, g is acceleration of gravity (9.8 m/s^2), P is pressure (1000 mb), R is the individual gas constant for dry air (2.87×10^6 erg/g/°K), and T is temperature (°K). This yields a variation of dP/dz from −0.12 to −0.11 mb/m over the temperature range of 0° to 30°C. Taking standard temperature (15°C), the critical gradient for trapping, in terms of potential refractivity is

$$\frac{dN_p}{dz} = -0.157 - (0.27)(-0.12) = -0.125 m^{-1} \tag{B-5}$$

Appendix C

IMPLEMENTING A MODIFIED EVAPORATION DUCT HEIGHT CALCULATION

Reference C-1 showed that a bias in air–sea temperature difference toward thermal stability resulted in spuriously high calculated evaporation duct heights. A modification to the duct height calculation that detected and compensated for the air–sea temperature difference bias was proposed based on the variation of duct height as a function of air–sea temperature difference at a constant relative humidity. To implement the algorithm, the value of either the air temperature or sea temperature may have to be changed to yield a modified air–sea temperature difference. A comparison of climatological air and sea temperatures from Marsden square data[C-2] and ocean data buoys[C-3] showed better agreement between sea temperature means than between air temperature means (Tables C-1 through C-5). Air temperature means from the Marsden square data also indicate a diurnal variation (~1°C) that the buoy data do not show. Mean air temperatures for 3-hour intervals for data buoys show diurnal variations of only a few tenths of a degree.* This gives more weight to holding sea temperature constant and varying air temperature to obtain the appropriate air–sea temperature difference.

The next question that arises, then, is whether or not it is reasonable to hold relative humidity constant while changing air temperature. Reed reported finding systematic errors in air temperature measurements aboard a ship but did not find systematic errors in relative humidity measurements.[C-4] Experience with psychrometric measurements in a thermal screen during the Ku-Band Surface Surveillance Project[C-5] sited on Point Loma in San Diego, tends to support Reed's findings. Recommendations of a working group on the computation of global air–sea flux climatology to use both daytime and nighttime humidities but only nighttime air and sea temperature lend support to the assumption of negligible bias in the relative humidity measurements.[C-6]

The implementation of the modified evaporation duct height calculation assumes that air temperature can be varied to obtain the appropriate air–sea temperature differences while sea temperature, wind speed, and relative humidity are held constant. Figure C-1 is a flow chart of the process.

* D. B. Gilhousen, National Oceanic and Atmospheric Administration Data Buoy Center, personal communication, January 1984.

Table C-1. Mean air and sea temperatures in °C for Marsden square 81 (day and night) and NOAA data buoy 42003 located 26.0 N 86.0 W.

Month	Air		Sea	
	MS81	42003	MS81	42003
Jan	22.2 21.2	19.4	24.0 24.0	23.7
Feb	22.0 20.7	19.8	23.6 23.5	24.2
Mar	23.8 22.4	21.9	24.1 23.9	24.8
Apr	24.7 23.7	23.9	25.1 25.0	25.7
May	26.5 25.5	25.4	26.6 26.5	26.6
Jun	28.0 27.0	27.7	28.2 28.2	28.5
Jul	28.9 27.9	28.2	29.1 29.1	29.3
Aug	28.9 28.0	28.2	29.4 29.4	29.3
Sep	28.6 27.6	28.0	29.0 29.0	29.1
Oct	27.1 26.0	25.9	27.9 27.9	27.9
Nov	25.0 23.9	23.7	26.4 26.4	27.0
Dec	23.4 22.3	21.5	25.1 25.1	25.9

Table C-2. Mean air and sea temperatures in °C for Marsden square 82 (day and night) and NOAA data buoy 42001 located 26.0 N 90.0 W and 42002 located 26.0 N 93.5 W.

Month	Air			Sea		
	MS82	42001	42002	MS82	42001	42002
Jan	19.7 18.5	19.2	18.8	21.4 21.4	22.5	21.6
Feb	19.8 18.6	19.1	18.6	20.8 20.8	21.6	20.8
Mar	21.7 20.5	20.6	20.2	21.5 21.3	21.3	21.2
Apr	23.2 22.3	22.8	22.4	23.0 23.0	23.3	22.9
May	25.3 24.2	25.2	24.8	25.2 25.1	25.7	25.1
Jun	27.7 26.7	27.6	27.5	27.8 27.8	27.8	28.1
Jul	28.8 27.9	28.5	28.6	29.3 29.3	29.1	29.5
Aug	28.9 28.0	28.6	28.6	29.5 29.4	29.4	29.8
Sep	28.2 27.3	28.0	27.8	28.9 28.8	28.8	29.0
Oct	26.2 25.0	26.0	25.5	27.1 27.1	27.1	27.6
Nov	23.5 22.5	23.8	22.9	25.1 25.1	25.1	25.4
Dec	21.4 20.4	21.7	21.0	23.0 23.1	24.1	23.3

Table C-3. Mean air and sea temperatures in °C for Marsden square 194 (day and night) and NOAA data buoy 46004 located 51.0 N 136.0 W.

Month	Air		Sea	
	MS194	46004	MS194	46004
Jan	5.9 5.4	6.5	6.7 6.6	6.8
Feb	5.8 5.1	5.8	6.5 6.4	6.3
Mar	6.2 5.2	6.0	6.2 6.3	6.2
Apr	7.3 6.3	6.2	6.6 6.7	6.5
May	9.1 7.6	7.5	7.8 7.8	7.7
Jun	11.0 9.8	9.6	9.7 9.7	9.7
Jul	13.3 12.3	12.2	12.0 12.0	12.2
Aug	14.7 13.6	14.0	13.5 13.7	14.2
Sep	14.0 12.7	13.5	13.2 13.1	13.7
Oct	11.3 10.3	11.4	11.4 11.2	11.8
Nov	8.1 7.4	8.9	9.2 9.0	9.6
Dec	6.4 6.1	6.6	7.6 7.7	7.6

Table C-4 Mean air and sea temperatures in °C for Marsden square 195 (day and night) and NOAA data buoy 46001 located 56.0 N 148.0 W.

Month	Air MS195	Air 46001	Sea MS195	Sea 46001
Jan	4.6 4.2	2.6	5.4 5.3	4.0
Feb	4.2 3.5	2.2	4.9 4.8	3.6
Mar	4.7 3.6	2.5	4.8 4.7	3.7
Apr	5.5 4.7	3.6	5.0 5.2	4.6
May	7.2 6.1	4.9	6.1 6.1	5.6
Jun	9.5 8.2	8.3	8.0 7.8	9.1
Jul	12.0 10.7	11.0	10.6 10.4	11.7
Aug	13.4 12.2	12.1	12.3 12.4	12.7
Sep	12.7 11.5	10.9	12.2 11.9	11.6
Oct	9.4 8.5	7.6	9.7 9.4	8.6
Nov	6.5 5.9	5.0	7.6 7.3	6.6
Dec	4.8 4.3	2.4	6.2 6.0	4.9

Table C-5. Mean air and sea temperatures in °C for Marsden square 196 (day and night) and NOAA data buoy 46003 located 52.0 N 156.0 W.

Month	Air		Sea	
	MS196	46003	MS196	46003
Jan	3.8	3.5	4.4	4.4
	3.4		4.4	
Feb	3.2	1.8	3.9	3.6
	2.3		3.7	
Mar	3.6	3.0	3.8	3.5
	2.7		3.7	
Apr	4.5	3.7	4.0	4.1
	3.3		3.9	
May	6.4	4.7	5.0	5.1
	4.9		4.9	
Jun	8.7	7.2	6.8	7.3
	7.1		6.6	
Jul	11.3	9.8	9.6	10.1
	9.8		9.4	
Aug	12.6	11.2	11.3	11.5
	11.3		11.1	
Sep	11.9	10.7	11.1	11.5
	10.5		10.9	
Oct	8.7	7.6	9.0	9.0
	7.7		8.9	
Nov	5.8	4.8	6.6	6.6
	5.0		6.7	
Dec	4.2	3.2	5.2	5.0
	3.6		5.1	

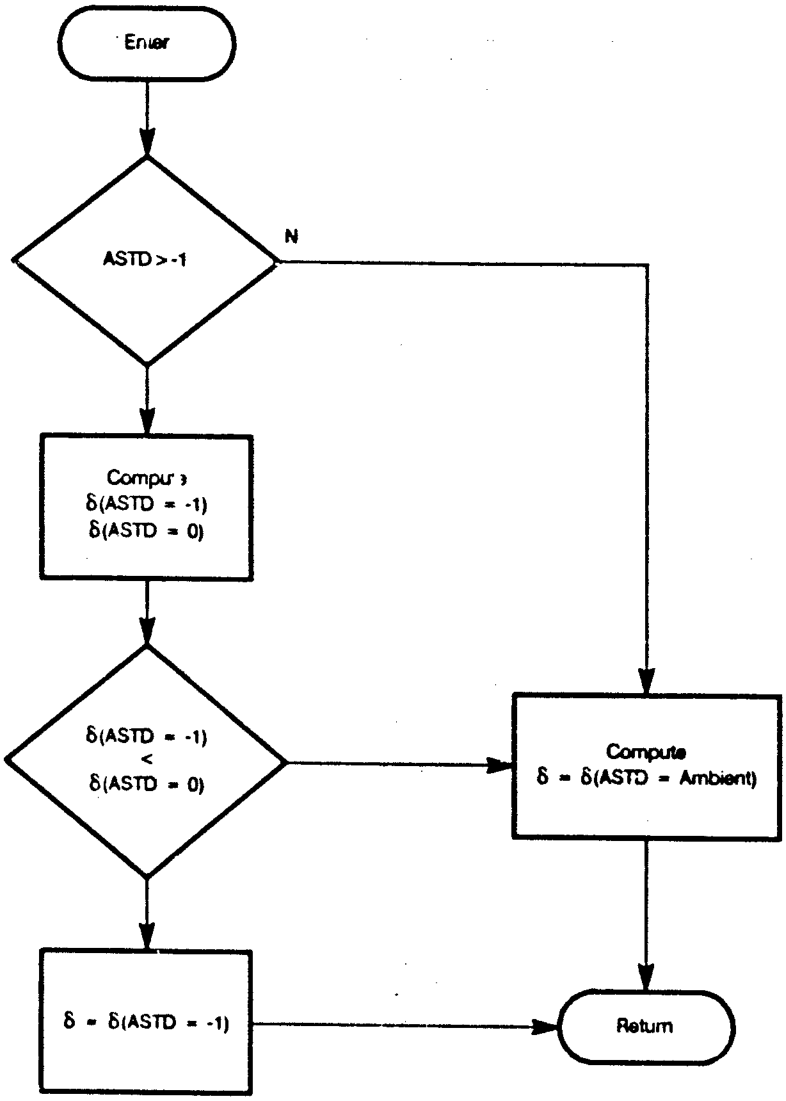

Figure C-1. Flow chart for the modified evaporation duct calculation based on air – sea temperature difference (ASTD).

REFERENCES TO APPENDIX C

C-1. Paulus, R.A., "Practical Application of the IREPS Evaporation Duct Model," Naval Ocean Systems Center TR 966, June 1984.

C-2. Naval Oceanography Command Detachment Asheville, "Evaporation Duct Report 76118," June 1981.

C-3. National Climatic Data Center, "Climatic Summaries for NOAA Data Buoys," January 1983.

C-4. Reed, R.K., "An Example of Shipboard Air Temperature Errors," *Mariner's Weather Log*, vol. 22, no. 1, pp. 13–14, January 1978.

C-5. Anderson, K.D., "Radar Measurements at 16.5 GHz in the Oceanic Evaporation Duct," *IEEE Transactions on Antennas and Propagation*, vol. 37, no. 1, pp. 100–106, January 1989.

C-6. Scoggins, J. R. and C. N. K. Mooers, "Workshop on Atmospheric Forcing of Ocean Circulation," *Bulletin American Meteorological Society*, vol. 69, no. 11 p. 1349–1353, November 1988.

Appendix D

FORTRAN PROGRAM TO CALCULATE EVAPORATION DUCT HEIGHT

```
c
c     ******************************************************
c     name:    delta.f

c     routine controls the execution of the 'get_delta'
c     function for testing the calculations of the evaporation
c     duct height (delta).

c     language: fortran iv ('77)
c     machine:  hp 520 (unix)

c     call sequence:
c         MAIN routine

c     glossary:
c         airt:   air temperature, deg C
c         seat:   sea temperature, deg C
c          rh:    relative humidity, %
c          u:     wind speed, knots

c     subroutines:
c          get_delta (function)
c          evap

c     rev    date     description
c     0.00   101987      -

c    ******************************************************
c     prompt the user for entries, call 'get_delta' to
c     compute the evaporation duct height
c    ******************************************************

      write(*,9000)
9000  format( "Compute the evaporation duct height from"/
     *         "entries of:"/
     *         " air temperature, deg C"/
     *         " sea temperature, deg C"/
     *          " relative humidity, % and"/
     *          " wind speed, knots"/)
```

```
      write(7,9010)
9010  format(". . air. . .|. sea . . .|. . rh. . .|. . . u . . . |.delta.|"/
     *        " temp   | temp    |   %    |   knots  | meters")

      do while(.true.)

        write(*,'("enter air temp (C): ",$)')
        read(*,*) airt

        write(*,'("enter sea temp (C): ",$)')
        read(*,*) seat

        write(*,'("enter relative humidity (%): ",$)')
        read(*,*) rh

        write(*,'("enter wind speed (knots): ",$)')
        read(*,*) u

        delta=get_delta(airt, seat, rh, u)

        write(7,9010)
        write(7,9020) airt,seat,rh,u,delta
9020    format(5f8.1)
      enddo

      end
```

```
c
c *****************************************************
c   name:    get_delta.f
c   routine calculates the evaporation duct height using
c    the paulus formulation "Practical Application of the
c    IREPS Evaporation Duct Model", NOSC TR 966, Jun 84
c   language: fortran iv ('77)
c   machine:  hp 520 (unix)
c   call sequence:
c       delta=get_delta(airt, seat, rh, u)
c   glossary:
c        airt:    air temperature, deg C
c        seat:    sea temperature, deg C
c         rh:      relative humidity, %
c         u:       wind speed, knots
c   subroutines:
c       evap
c   rev    date          description
c   0.00   101987     modify 'duct63' program code to
c                     make a stand-alone utility.
c *****************************************************

      function  get_delta(airt,seat,rh,u)

c *****************************************************

c   check wind speed, convert to deg K, and compute
c   vapor pressures

      if (u .gt. .01) then

         wvel=amax1(1.0, u)

         dtok=273.2

         tak=airt+dtok
         tsk=seat+dtok

         esw=6.105*exp(25.22*seat/tsk-5.31*alog(tsk/dtok))
         es  =6.105*exp(25.22*airt/tak-5.31*alog(tak/dtok))
          e  =rh*es/100.
```

```
c     calculate delta

        t1=tsk-1.0              !modified air tem
        if(tak .gt. t1) then
          e1=rh*esw/100.
          call evap(wvel,tsk,tsk,e1,esw,del0)
          es1=6.105*exp(25.22*(seat-1.0)/t1-5.31*alog(t1/dtok))
          e1=rh*es1/100.
          call evap(wvel,t1,tsk,e1,esw,delta)
          if(del0-delta .lt. 0.) then
            call evap(wvel,tak,tsk,e,esw,delta)
          endif
        else
          call evap(wvel,tak,tsk,e,esw,delta)
        endif

      else

         delta=0.

      end if

      return

      end
```

```
c ****************************************************
c
c  Name:  EVAP
c
c  Routine calculates the evaporation duct height
c  (in metres) following the method of Jeske "The State
c  of Radar Range Prediction over Sea", Tropospheric
c  Radio Wave Propagation - Part II, NATO-AGARD, Feb 71
c
c  Language:   FORTRAN IV ('77)
c  Machine :   Univac 1100/82
c
c     CALL Evap(wvel,tak,tsk,e,esw,delta)
c
c     wvel:   Wind speed knots
c     tak:    Air temperature in Kelvin
c     tsk :   Sea temperature in Kelvin
c     e   :   Vapor pressure mbs
c     esw :   Surface vapor pressure mbs
c     delta   Duct height m RETURNED
c
c  Rev  Date     Description
c  0.0  052984      -
c
c ****************************************************
c
      subroutine evap(wvel,tak,tsk,e,esw,delta)
c
      real lnz1z0
c
c ----------------------------------------------------
c
      delta=0.              !default duct height
      z0=1.5e-4             !roughness height
      z1=6.                 !reference height (m)
      beta=4.5              !constant
      alpha=5.2             !constant
      lnz1z0=alog(z1/z0)    !useful
      b1=-0.125             !potential refractivity trapping grad.
c
c ----------------------------------------------------
```

```
c
      rib=369.*z1*(tak-tsk)/(tak*wvel*wvel)
      if(rib .gt. 1.) rib=1.
c
c     compute potential refractivity difference
c
      delna=77.6/tak*(1000.+4810.*e/tak)
      deln0=77.6/tsk*(1000.+4810.*esw/tsk)
      deln=delna-deln0
      if(deln .ge. 0.) return
c
c --------------------------------------------------------------
c     compute the gamma function
c
      if(rib .le. -3.75) then
        gamma=0.05
      else if(rib .le. -0.12) then
        gamma=0.065+rib*0.004
      else if(rib .le. 0.14) then
        gamma=0.109+rib*0.367
      else
        gamma=0.155+rib*0.021
      end if
c
      olp=rib/(10.*z1*gamma)          !1./L'
      z1olp=z1*olp
c
c --------------------------------------------------------------
c     compute Psi function for unstable conditions
c
      if(rib .lt. 0.) then
        if(z1olp .ge. -0.010) then
          psi=-4.5*z1olp
        else if(z1olp .ge. -0.026) then
          psi=10.**(1.020*alog10(-z1olp)+0.690)
        else if(z1olp .ge. -0.100) then
          psi=10.**(0.776*alog10(-z1olp)+0.306)
        else if(z1olp .ge. -1.000) then
          psi=10.**(0.630*alog10(-z1olp)+0.160)
        else if(z1olp .ge. -2.200) then
          psi=10.**(0.414*alog10(-z1olp)+0.160)
        else
          psi=2.000
        end if
```

```
c
c    Compute unstable delta
c
       b=lnz1z0-psi
       btemp=b*b1/deln
       d=btemp**4 - 4.*beta*olp*btemp**3
      if(d .gt. 0.) delta=d**(-0.25)
c
c    Stable and neutral conditions
c
     else
      b=lnz1z0+z1olp*alpha
      delta=deln/(b*b1 - alpha*deln*olp)
      if(delta .lt. 0. .or. delta*olp .gt. 1.) then
          delta=(deln*(1.+alpha)-b1*alpha*z1)/(b1*lnz1z0)
       end if
     end if
c
c    Return to caller
c
     return
c
     end
```

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